Self-consistent Radial Electric Field and Neoclassical Transport

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The standard neoclassical transport theory is routinely compared with tokamak experimental results. In internal transport barrier region where plasma gradient is so steep that ion orbit width is comparable to the gradient scale length, ion thermal transport is observed to be significantly lower than the neoclassical level. Under these conditions, however, the standard neoclassical theory must be modified by the effects of finite orbits and the radial electric field. Without a self-consistent radial electric field, neoclassical particle transport is not ambipolar because of self-collision driven ion flux; ambipolarity requires the development of a radial electric field $E_{\rm r}$. The electric field in turn affects the collisional transport rates through finite orbit effects, even though the neoclassical transport rates do not depend on the radial electric field in the limit of small orbit width. Here, neoclassical transport with finite ion orbits is studied, including for the first time, the self-consistent radial electric field, using a low noise delta-f particle simulation. We show how a self-consistent electric field guarantees neoclassical ambipolarity. We demonstrate the general feature of $E_{\rm r}$ dynamics: geodesic acoustic oscillations appear in the initial phase and then relax to a neoclassical quasi-steady-state through different damping mechanisms; the neoclassical $E_{\rm r}$ is subjected to further relaxation in transport time scale to equilibrium through angular momentum transport. The state-state $E_{\rm r}$ is found, regardless of the steepness of the density profile, to be consistent with the standard neoclassical expression for parallel flow(for uniform temperature and zero toroidal rotation, the expression reduces to the Boltzmann relation). A deep electric field well (with strong shear) is found in a region with steep density gradient. Ion thermal transport is reduced on the side of the well with negative $E_{\rm r}$ shear and increased on the outer side with positive shear, relative to the standard neoclassical level. This is consistent with the orbit squeezing effect of the $E_{\rm r}$ and is observed for the first time in numerical simulation. Also, the ion heat flux near the magnetic axis is largely reduced by the effects of finite orbits and the electric field. Preliminary results show that strongly sheared $E_{\rm r}$ and, possibly, sheared toroidal flow may modify the standard neoclassical poloidal flow through finite orbit effects.

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